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ASSEMBLY AND LIFTING OF PEARL-CHAIN ARCHES

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Abstract

Pearl-Chain arches were invented at the Technical University of Denmark in cooperation with the company Abeo A/S. The system uses specially designed, pre-fabricated concrete elements that are post-tensioned together into an arch shape, which is then lifted into place. The arches can be used both in buildings and bridges.

The assembly and lifting of two Pearl-Chain arches, with a span of 13 m and rise of 1 m, is considered in this paper. Precast “Super-Light Deck” elements were used for the arches, which had a thickness of 22 cm. Both arches were successfully lifted, rotated in mid-air, and placed adjacent to one another on prepared footings. The arches’ span and shape were continuously monitored during the entire construction sequence, and deformations stayed within an anticipated level.

Keywords: Pearl-Chain Bridge, Post-tensioning, Super-Light concrete decks, full-scale testing, pre-fab elements, arch erection method, Hammerhead joints.

1 Introduction

Pearl-Chain (PC) arches consist of a number of straight pre-fabricated concrete elements called Super-Light (SL) decks which are post-tensioned together into a desired shape (Halding & Hertz 2015; Hertz & Halding 2014).

The SL-deck technology uses normal concrete (cylinder compressive strength of 55 MPa, and density of 2300 kg/m³) in combination with a lightweight aggregate concrete (cylinder compressive strength of 3 MPa, and density of 700 kg/m³). SL-decks are produced by pouring the normal concrete over lightweight aggregate concrete blocks. Using lightweight concrete reduces the weight of the elements without compromising their rigidity or stability (in contrast to using thinner slabs). Therefore, a lower capacity crane can be used to safely erect the arches. However, normal, strong concrete is used for the full slab thickness at the ends of the SL-decks where compressive stresses need to be transferred from one SL-deck element to the next. The use of the lightweight aggregate concrete also makes the construction more environmentally friendly (Hertz & Bagger 2011).

A whole PC bridge would consist of several PC arches next to each other, giving the desired bridge width. The following challenges are posed for the assembly and erection of each arch:

First of all, the assembly of SL-deck elements on the ground is essential. To reach the correct shape, each SL element must be positioned accurately before being post-tensioned, and not to significantly change shape due to the post-tensioning. Each PC arch in a bridge must be identical concerning the span and shape, since even small errors in the geometry will be visible after erection.

Secondly, the arches need to have sufficient moment capacity to withstand the static and dynamic loading while lifted by crane. Special attention has to be given to the position of lifting

points and the lifting method. The weight of the arches should also be minimized in order to reduce the bending stresses during lifting, and to be able to lift with a larger lever arm of the crane.

Thirdly, the distance between the abutments has to be sufficiently large for the arches to be placed correctly – even when being slightly deformed hanging from a crane. Placing an arch requires the abutment not to settle horizontally more than intended, since even relatively small unneeded horizontal movements can significantly increase the bending moment in an arch. Therefore, the abutments must be placed far enough from each other to accommodate any deformations due to lifting. In a perfect lifting process the arch span should be slightly shorter when being put into position. This means that the lifting points are moved a bit toward the middle of the arch, and a negative moment is introduced in the structure. This can be good from a static point of view, but of course both the sub-structure and super-structure must be prepared. The test arches are two-hinged, with a hinge at each of the springings.



Fig. 1 Four-point transportation of a 13 m Pearl-Chain arch by truck.

1.1 Previous assembly and lifting methods

Prior to the middle of the 20th century, all concrete arch bridges were cast in situ, which requires significant time and energy for formwork and scaffolding construction. Increasing labor costs have created a market for pre-fabricated bridges, and the following pre-fabricated concrete arch bridges are examples of this:

TechSpan produces pre-cast concrete arch bridges with higher rise (relative to PC arches), and with spans of up to approximately 20 m. They assemble their arches from two smaller pieces put together. This requires one crane per arch half, and hence, two small cranes are required for the erection of at least the first two full arches. The arch segments are lifted at four points. Finally, the crown (the top of the arch where the pieces meet) is grouted (Hutchinson 2004; Proctor & Seow 2000). Similar to a Pearl-Chain bridge, the width of a TechSpan arch bridge can be increased by simply adding more arches adjacent to each other.

BEBO is another manufacturer of pre-cast concrete arch bridges. Their system is similar to Techspan's, but permits spans up to 30 m. For spans over 14.6 m they use a twin leaf method that requires two cranes for erection. The crown is cast in situ (Bernini et al. 2000; Bebo 2014).

The Nucon arch system differs from the above in regard to its assembly and lifting. Straight pre-cast concrete segments are placed flat on the ground, which are chained to a specially designed

lifting beam. An arch consists of several smaller pieces (similar to PC arches), and the arch does not take the intended shape until the lifting beam is elevated by a crane (Wakeman 1995).

Macrete Flexiarch uses even more smaller concrete segments than the Nucon arch system. All the segments are connected by a flexible membrane bonded to the top of all the elements. The arch, like the Nucon arch, is flat when on the ground, and obtains its design shape when being lifted. The longest available Flexiarch has a span length of 17 m, and requires six lifting points, including two at the crown (Macrete 2014; Mokhtar et al. 2011).

1.2 Scope

The assembly, lifting, and final placement of the first 8-element Pearl-Chain arches of 13 m is assessed in this paper. Lifting points were found by FE modeling in order to minimize bending moments (not presented in this paper). Different ways of placing the arches are also evaluated: both by use of wedges and by hydraulic flat jacks.

2 Positioning and post-tensioning the elements

The 13 m Pearl-Chain arches for testing of the assembly procedure consisted of six Super-Light deck elements, and two specially designed abutment-elements. All the elements had an interior cable duct for a 7C15 post-tensioning cable. Fig. 2 shows an overview of the components in one arch. The elements were cast at least seven days before the assembly.

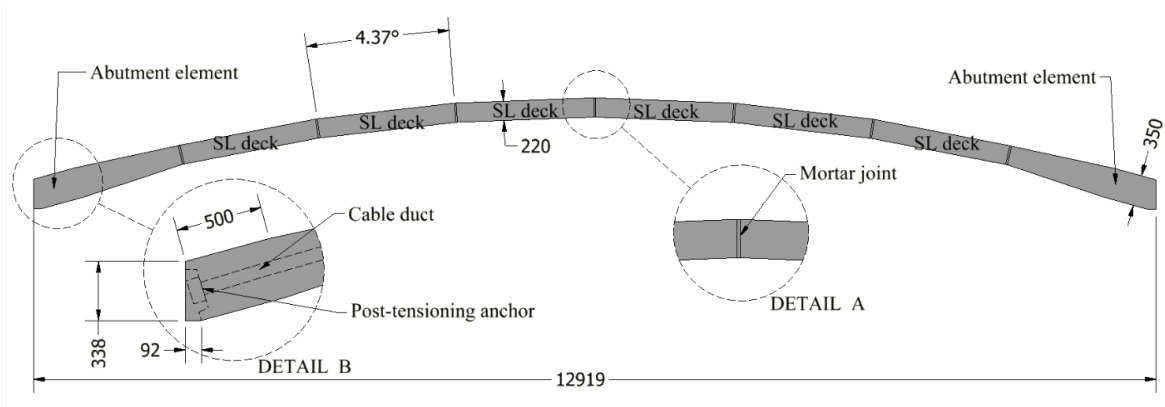


Fig. 2 One PC arch consisting of six SL-elements and two abutment elements. It is held together by a post-tensioning cable running through all the elements. Detail A shows a mortar joint at the crown, and similar joints exist in all element connections. The rise is 1 m, and all units are mm.

The width of each test arch was 1.75 m, and the SL-deck elements were 220 mm thick. Other SL-deck widths and thicknesses are possible. The thickness of the abutment elements was tapered from 350 mm at the anchorage end for the post-tensioning (500 mm from the anchorblock location) to 220 mm at the connection to the SL-decks.

All elements were pre-cast, transported to the site, and then placed on their edge on shims on the ground for post-tensioning. Ends of cable ducts from each element were connected and formwork was put up for in situ casting of the mortar joints between the elements. The compressive cylinder strength of the mortar was: >20 MPa after 24 hours, >60 MPa after 7 days, and >80 MPa after 28 days. The mortar was designed and tested to remain homogeneous when being poured over a height of up to 2.4 m (Lund et al. 2014).

Two days later, the mortar was hardened enough for the post-tensioning to take place. The cable was post-tensioned to 90 % of the 0.1 percent proof strength of the steel, giving a force of 221 kN per wire. This force will decrease over time with up to 20 % due to anchorage seating loss, shrinkage, creep, and relaxation. See Fig. 3 for pictures of the assembly steps.

The last part of the pre-lifting assembly was grouting the cable duct.



Fig. 3 Assembly steps for PC arch. 1) Top left: Vertical positioning of the elements in the desired arch shape. The dark surfaces are light aggregate concrete blocks. 2) Top right: Formwork put up and joints are cast between elements. 3) Bottom left: Two days later the formwork is removed and post-tensioning is performed. 4) Bottom right: Grouting of cable duct and the arch is ready for lifting.

This method was selected in order to minimize crane time, which is often a costly component of bridge construction. If the PC arches were assembled on temporary scaffolding or on a ground excavation (that followed the arch profile), a large, mobile crane would be required to lift and erect the arch before the next arch assembly could begin. By assembling each arch on its side, a smaller, less expensive crane mounted on a truck can be used to handle the individual SL-elements. After assembling several PC arches, a larger crane can then be brought to the site to erect all the arches at the same time.

3 Lifting process of one arch

The optimal lifting method was determined on beforehand with analyses in the FE program: Autodesk Robot Structural Analysis, and by simple hand calculations (not presented in this paper). Mid-air rotation of the arch was necessary, and the number and position of lifting points were studied to minimize bending moments during the lift. The lifting sequence can be summarized as:

- 1) Using two lifting points to vertically lift the arch from its “on-side“ orientation.
- 2) Connecting two additional lifting points, and then rotating the assembly in mid-air.
- 3) Transporting the arch in its horizontal orientation.

At first the arch was lifted in two points. This first vertical lift should be performed without the arch slanting to the side when leaving its supports. The balance points were found to be slightly into the first SL-decks next to the abutment elements.

When hanging in the air, the arch was then rotated and transported to the site of erection. Rotating and lifting the arch in its horizontal orientation with the same lifting points used for the

initial vertical lift resulted in bending moments less than the arch's capacity. Therefore, the same lifting points were chosen for both vertical and horizontal lifting (although two additional points were added for the horizontal lift). The optimal position for the four-point, horizontal lifting of the arch is two points approximately in the middle of the first SL-decks adjacent to the abutment elements on each end. However, positioning the lifting points here was not chosen due to the light-aggregate concrete in the SL-decks in this area. Fig. 4 shows the position of the final lifting points.

A factor of 1.65 was applied to the static analysis results in order to account for dynamic loading.



Fig. 4 Top: Lifting points for PC arch (circled in red). The two top points were used for the initial vertical lift. Bottom: Subsequently, the two bottom lifting points were connected, and the arch was rotated, positioned on temporary supports, and transported by truck to the erection site.

During this assembly and lifting test, the mid-air rotation was performed by a small crane as well as a large truck working together. They lowered the arch onto a temporary support, supporting the arch at the $\frac{1}{4}$ points. Thereafter, the truck could lift and transport the arch to the erection site, see Fig. 1. In future Pearl-Chain bridge erections, such maneuvering can be performed with one mobile crane alone, by means of a crane hoist. In future Pearl-Chain bridges, the arch elements should be assembled next to the erection site so that the total number of arches for the PC bridge can be lifted and put on prepared foundations one by one with a mobile crane.

4 Positioning and post-lifting assembly

Positioning of the arches on a prepared foundation was a significant part of the assembly process. As seen in Fig. 2, the theoretical span for an arch alone is less than the 13 m, and this is because of the need for space between the foundation and the arch when positioning it on the foundation. Arches transfer horizontal forces as well as vertical forces to the abutments, so the positioning has to be precise, since even small horizontal settlements of the arch springings will incorporate undesired bending moments in the arch.

Two methods were tried when positioning the arches: The first PC test arch was positioned on the foundation, and plastic and wood wedges were put in the space to regulate the span length. The span of the second PC test arch was adjusted by two hydraulic flat jacks at each springing. The latter method was less time consuming.

The remaining space between the arches and the foundation was later cast out with a mortar. Because the springings were designed to behave as hinges, no reinforcement was used between arches and footings. Fig. 5 shows the two methods for positioning the arches at the foundation.



Fig. 5 Connection detail between foundation and arch. Left: First PC test arch was connected by plastic pieces and wood wedges. Right: Second PC test arch was connected by pumping up hydraulic flat jacks (requiring 6 bars of pressure).

After the placement, the two arches were tied together with shear connections called “Hammerhead joints“, which were prepared on the side of every SL-deck element. The Hammerhead joints consisted of a transverse, 550 MPa Y12 reinforcement steel bar embedded in a recess formed in the strong concrete. The steel bar goes from the concrete into the Hammerhead recess where it bends 180 degrees (with a bending radius of 96 mm) and continues back into the concrete again, see Fig. 6. The recess length was 500 mm, the depth was 113 mm, and the width was 110 mm. After placing the second arch, the Hammerhead joint recesses of each arch became aligned with each other and pieces of rebar were put on the inside of the bended Y12 in the longitudinal direction. Then, the longitudinal rebar pieces were connected by a rebar hoop that went around both bars. The longitudinal bars and the hoops were both 550 MPa Y16. Finally, the whole thing is cast out with a >55 MPa mortar. The arches are positioned 10 mm apart, and therefore it is necessary to use a construction foam as a formwork between the two arches to contain the mortar during the Hammerhead joint pour.

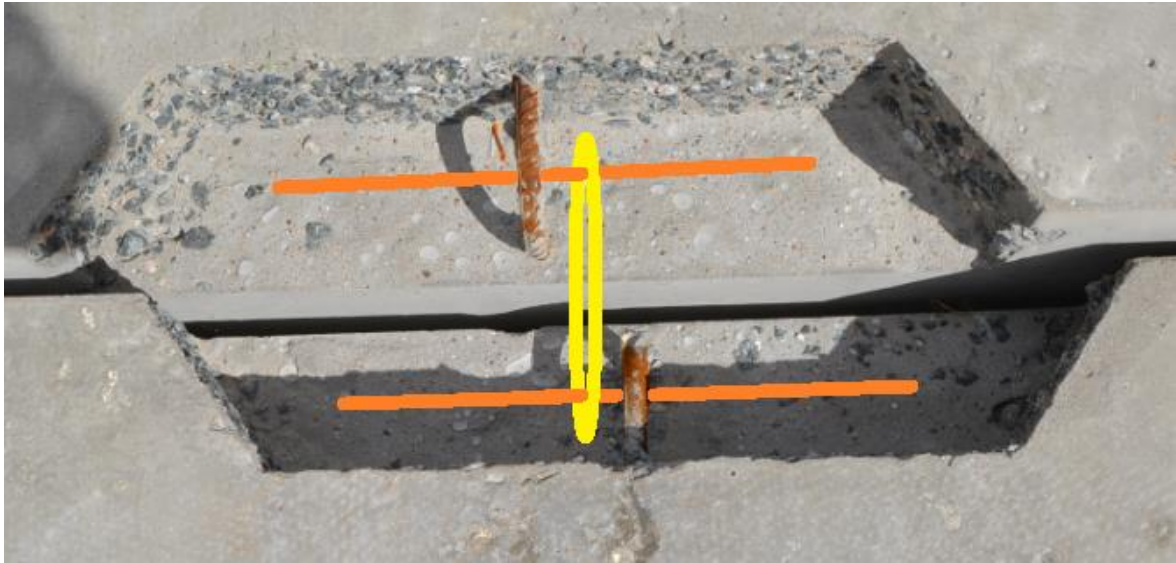


Fig. 6 Hammerhead joint recesses on sides of two adjacent SL decks before assembly. Y12 rebars are seen on both sides. Later longitudinal bars (drawn in orange), a steel hoop (drawn in yellow), and construction foam will be applied before pouring the mortar. The aggregates are exposed for better shear transfer.

Each Hammerhead joint can transfer a shear force of more than 2.5 tons. Due to the hoop around the longitudinal bars, the joint remains functional even if the arches are not perfectly aligned.

5 Lessons learned

Shortly after the post-tensioning of both arches, visible cracks were formed in the longitudinal direction through the mortar joints between the elements. The cracks were only found between SL-decks and not at the joints to the abutment elements. They also only occurred in the bottom face of the elements, see Fig. 7.

When the arches were post-tensioned with a cable through the curved ducts in the elements, the curvature of the cable resulted in a downwards force along the duct. Increasing the deck thickness and the cross reinforcement will increase the crack resistance. Also, the curing time of the concrete and mortar before post-tensioning has an influence (in this case the curing time was less than two days). In a previous test where the concrete had been cured for a longer time these cracks did not appear although the thickness of the deck and the prestressing force were identical. In future PC arches additional reinforcement will be applied transversely below the ducts in the SL decks and sufficient curing time will be applied to avoid any cracking which potentially could lead to corrosion of the tendon.



Fig. 7 Crack forming in the longitudinal direction in the bottom of the SL-deck in the joints between SL-elements. Joints between abutment elements and SL-decks did not crack due to larger number of transverse reinforcement. The dark areas are the bottom of the light aggregate concrete blocks.

Before and after the assembly and lifting of both PC arches, the arch span lengths were measured, see Table 1. Before post-tensioning, the span length was within 10 mm of the design shown in Fig. 2. After positioning the arch on the foundation, the span lengths ended up being 15 mm longer than after the post-tensioning had been completed. In addition to the above measurements, arch 2 were measured right after post-tensioning as well as in mid-air during the transportation.

Table 1
Span of the two PC arches in the assembly and lifting test.

Time	Span of arch 1 (m)	Span of arch 2 (m)
Before post-tensioning	12.910	12.910
After post-tensioning, before lifting	-	12.885
During lifting: hanging at four points	-	12.880
Final position with wedges/flat jacks	12.900	12.900

A deformation of 15 mm was within the expected range for the span after post-tensioning compared with the span at the final position. The first arch was lifted the day after the post-tensioning, and the second arch was lifted three weeks after the post-tensioning. Possibly, creep could be a small part of the reason why the first arch, ended up with a 25 mm lower rise than the second arch when they were placed next to each other. Though this difference was easily observed, it did not affect the structural behavior except for the “built-in” bending moments, since the Hammerhead joints were designed to provide some tolerance for misalignment. Two other significant reasons for the difference in the rise was measuring accuracy of more than ± 5 mm when measuring the span, and inaccurate assembly by the workman crew. Fig. 8 shows the misaligned arches and Hammerhead joints.



Fig. 8 Top: Close up of difference in height between the two arches at the crown showing the requirement of high accuracy during the assembly process. The first arch (closest) was placed on the foundation three weeks prior to the second arch (furthest away). Bottom: The first 13 m span PC arches in their final position.

6 Conclusion

Two 13 m span Pearl-Chain arches were successfully assembled, post-tensioned, lifted, and positioned on a prepared foundation. Each arch was composed of eight pre-fabricated, Super-Light deck elements. The arches were placed adjacent to one another, and formed a single span bridge.

The arches were assembled by first placing the elements vertically (on edge) in the desired arch shape before casting the joints between the elements with a fluid mortar. Two days later, post-tensioning took place, and one arch was measured to reduce its span by 25 mm due to the post-tensioning. Minutes after the post-tensioning, longitudinal cracks developed in the mortar joints under the cable ducts; the cracks were investigated and assessed to only have aesthetic concern in regard to the rest of the test.

Lifting, including mid-air rotation, went smoothly for both arches, and two different methods were tried when placing the arches on the foundation. The method using flat jacks was less time consuming.

In the final position, the arch span length was within 15 mm of the span lengths measured after post-tensioning (for arch 2). This produced “built-in” bending moments in the arches, but the deformations were within the expected limit of deviation for the span. The final rise of the arches differed by 25 mm at the crown. The main reason for the difference was span measuring inaccuracy

and assembly errors by the workman crew. The two arches were tied together with Hammerhead joints, which were designed to permit some misalignment between the arches. The joints were completed without incident.

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